NASA TECHNICAL MEMORANDUM

PARAMETRIC TEST RESULTS OF A
SWIRL-CAN COMBUSTOR

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ABSTRACT

Pollutant levels of oxides of nitrogen, unburned hydrocarbons and carbon monoxide were measured for three models of an experimental, annular swirl can combustor. The combustor was 1.067 meters in outer diameter, incorporated 120 modules and was specifically designed for elevated exit temperature performance. Test conditions included combustor inlet temperatures of 589, 756 and 839 K, inlet pressures of 3 to 6.4 atmospheres, reference velocities of 21 to 38 meters per second and combustor equivalence ratios, based on total combustor flows of 0.206 to 1.028. Maximum oxides of nitrogen emission index values occurred at an equivalence ratio of 0.7 with lower values measured for both higher and lower equivalence ratios. Oxides of nitrogen concentrations, up to the 0.7 level with 756 K inlet air, were correlated for the three models by a combined parameter consisting of measured flow and geometric parameters. Effects of the individual parameters comprising the correlation are also presented.

INTRODUCTION

This report presents measured combustor exhaust pollutant levels of oxides of nitrogen, unburned hydrocarbons and carbon monoxide, describes factors controlling their formation, presents a correlation of the oxides of nitrogen based on measurable flow and geometric parameters, and demonstrates reductions in oxides of nitrogen attainable with a swirl can combustor.

Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by gas turbine engines. Two general areas of concern have been expressed: urban pollution in the

vicinity of airports and pollution of the stratosphere. The principal urban pollutants are unburned hydrocarbons and carbon monoxide during idle and taxi, and oxides of nitrogen and smoke during take-off and landing. Oxides of nitrogen are also considered to be the most predominant emission products formed during altitude cruise.

Altering gas turbine combustor designs to make substantial reductions in oxides of nitrogen will be an extremely difficult task, reference 1. Oxides of nitrogen are formed during any combustion process involving air. The amount formed is reaction rate controlled and is a function of flame temperature, dwell time of the combustion gases at high temperatures, concentrations of nitrogen and oxygen present and, to a somewhat lesser extent the combustor pressure. Flame temperatures increase as the combustor inlet temperature increases and as the primary zone fuel-air ratio approaches stoichiometric values. Dwell time is affected by combustor primary zone length and reference velocity. Trends in combustor operating conditions indicate a steady increase in inlet temperature due to increasing compressor pressure ratios, reference 2.

Past studies of swirl-can combustors, references 2 and 3, have indicated that this combustor type offers several inherent advantages for reducing oxides of nitrogen. These advantages include:

1. Short combustor lengths with accompanying short recirculation zones are realized for burning and mixing. Thus dwell time is reduced.

2. Quick mixing of burning gases and diluent air occurs inasmuch as swirl-can combustors pass nearly all of the air flow through the primary combustion zone and large interfacial mixing areas exist between combustion gases and airflow around the swirl-cans.

3. Premixing of fuel and air occurs upstream of the burning zone and produces a more uniform mixture of fuel and air thereby reducing localized intense burning. This effect is reinforced by the large number of fuel entry positions.

The swirl-can combustor used in these tests was designed for operation up to stoichiometric fuel-air ratios. Most of the pollution data were obtained during the testing to stoichiometric conditions. Some data were also obtained

parametrically to illustrate the effects of reference velocity and inlet air temperature upon formation of oxides of nitrogen. Data previously reported in reference 4 are also included at a simulated engine idle condition to illustrate how pollutant levels of unburned hydrocarbons and carbon monoxide can be successfully minimized by fuel staging. Pollutant concentrations of nitric oxide (NO), oxides of nitrogen (NO + NO_2), unburned hydrocarbons and carbon monoxide are presented for the following spans of test conditions: Combustor inlet air temperatures 589, 756 and 839 K; inlet pressure, 3 to 6.4 atmospheres; equivalence ratios of 0.206 to 1.028 and reference velocity, 21 to 38 meters per second.

APPARATUS AND PROCEDURE

Test Facility

Tests were conducted in a connected-duct component test facility at the Lewis Research Center. The details of the test facility and instrumentation are contained in appendixes A and B of reference 5.

Combustor Design

The test combustor, shown in figures 1 and 2 is an annular design 0.5143 meters long from the diffuser inlet to the combustor exit plane, and is 1.067 meters in outer diameter. The combustor is a swirl-can design and incorporates several unique features including a combustor module array. The array consists of 120 modules, positioned on three circumferential rows, which distribute combustion uniformly across the combustor annulus. All of the combustor airflow, exclusive of liner coolant flow passes through the array thus providing an abundance of air for all stages of the combustion process, as well as providing the capability for quick mixing of hot gases and diluent air. The only airflow introduced downstream of the array is liner cooling air which accounted for 4 to 7 percent of the total airflow. Performance of a prior model of this combustor over an extended exit temperature span has been described previously in reference 3.

Combustor Modules

A typical combustor module is shown schematically in figure 3. Each module consists of three components; a carburetor, swirler and flame stabilizer. In operation, the modules perform several functions. Each module premixes fuel with air, swirls the mixture, stabilizes combustion in its wake and provides large interfacial mixing areas between the bypass air through the array and combustion gases in the module wake.

Combustor Models

Three combustor models are discussed in this paper. Combustor modules for these models are shown in figure 4. All models utilized the same carburetor and swirler design and differ only in flame stabilizer design. Flame stabilizer designs were varied to determine the effects of blockage variations and effects of variances in interfacial mixing area. Combustor model 1 employed two types of flame stabilizers which produced a combustor blockage of 60.6 percent and a module effective wetted perimeter of 5.114 cm. Combustor model 2 produced blockages of 63.5 percent and a wetted perimeter of 5.156 cm. Combustor model 3 produced a combustor blockage of 47.9 percent and had a wetted perimeter of 4.409 cm. Blockages were based on the total flow area in the plane of the flame stabilizers. Wetted perimeters were calculated by the ratio of 4 times the area of the flam stabilizer minus the swirler geometric flow area divided by the perimeter of the flame stabilizer.

Test Conditions

All tests were conducted with ASTM-A1 liquid fuel. The fuel had an average hydrogen-carbon ratio of 0.161 and lower heating value of 18 600 Btu per pound.

Tests were conducted over a range of equivalence ratios of 0.208 to 1.028. For combustor exit average temperatures below 1530 K, a 5-point radial traverse temperature and pressure rake was used to evaluate com-

bustor performance, and all flow conditions of interest could be investigated. A choked nozzle was used to measure combustor performance for higher exit temperatures. Reference velocities were limited by the choked nozzle and with a 589 K inlet air temperature varied from 30.5 meters per second at an exit temperature of 1200 K to 21 meters per second at an exit temperature of 2300 K. Reference velocities for higher inlet air temperatures were proportionately affected. The test facility had a maximum pressure limitation of 6.5 atmospheres.

Exhaust Gas Pollutant Sampling

Concentrations of nitric oxide, total oxides of nitrogen, carbon monoxide, unburned hydrocarbons and carbon dioxide were obtained with an on-line system. All samples were drawn from one circumferential location and at three radial locations at the combustor exit through the water cooled probe shown in figure 5.

Gas Sample System

Approximately 9 meters of 3/8 inch stainless steel line was used to transport the sample to the analytical instruments. In order to prevent condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was electrically heated to 427 K. Sample line pressure was maintained at 10 psig in order to supply sufficient pressure to the instruments.

The exhaust gas analysis system, shown in figure 6, is a packaged unit consisting of four commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. In addition to visual readout, electrical inputs were provided to the IBM 360 computer for on-line analysis and evaluation of the data.

The hydrocarbon content of the exhaust gas was determined by a Beckman Instruments Model 402 total Hydrocarbon Analyzer. This instrument is of the flame ionization detector type.

Concentrations of oxides of nitrogen were determined by a Thermo Electron Corporation Model 10A Chemiluminescent analyzer. The instrument included a thermal convertor to reduce nitrogen dioxide to nitric oxide and was operated at 1290° F.

Both carbon monoxide and carbon dioxide analyzers were of the nondispersive infra-red (NDIR) type (Beckman Instruments model 315B). The CO analyzer had four ranges: 0-100 ppm, 0-1000 ppm, 0-1 percent, and 0-10 percent. This range of sensitivity was accomplished by using stacked cells of 0.25- and 13.5-inch length. The CO_2 analyzer had two ranges, 0-5 percent and 0-15 percent, with a sample cell length of 0.125 inches.

<div align="center">Analytical Procedure</div>

All analyzers were checked for zero and span prior to tests. Since the analyzer console required only a few seconds for each instrument to switch from calibration to sample modes, it was possible to perform frequent checks to insure the calibration accuracy without disrupting testing.

Where appropriate, the measured quantities were corrected for water vapor removed. The correction included both inlet air humidity and water vapor from combustion. The equations used were obtained from reference 6.

The emission levels of all of the constituents were converted to an emission index parameter. Emission index values were computed from the measured quantities as proposed by the SAE Committee E-31 (ref. 6). An alternate procedure based on metered fuel-air ratio was also employed. Using the latter technique, emission index values for any constituent, X, can be calculated by the following expression:

$$EI_x = \frac{M_x}{M_a} \frac{1 + f}{f} (x) \times 10^{-3}$$

where

EI$_x$ emission index in grams of X/kg of fuel burned

M$_x$ molecular weight of X

M$_a$ molecular weight of air

f   metered fuel-air ratio

(x)   measured concentration of X in ppm

Both procedures yield identical results when the sample validity was good.

Since practical considerations limited exhaust gas sampling to only one circumferential location, attempts were made to verify that the gas sampling position was representative of pollutant levels at the combustor exit. Two fuel-air ratios were calculated. The first value was computed from measured quantities of carbon dioxide, carbon monoxide, and unburned hydrocarbons. The second fuel-air ratio was obtained from metered values of fuel and air. Fuel-air ratios obtained by both methods are shown in figure 7. All of the data presented in this report, for which both values of fuel-air ratio were available, produced gas sample fuel-air ratios within plus or minus 15 percent of metered values.

RESULTS AND DISCUSSION

Test Results

Oxides of nitrogen. - Nitrogen oxides are formed during any combustion process involving air. These oxides, commonly referred to as NO_x, consist primarily of nitric oxide (NO) and significantly lesser amounts of nitrogen dioxide (NO_2). NO concentrations and NO_x concentrations expressed in parts per million for all three combustor models are shown in figure 8. Test conditions were inlet-air temperatures of 589, 756 and 839 K, a reference velocity span of 21 to 36.6 meters per second, inlet pressures of 4 to 6 atmospheres and a combustor exit temperature span of 1140 to 2320 K. In spite of the wide variances in test conditions, nearly all of the data appear to fall along a straight line indicating that the formation rate of NO_2 is constant. Exceptions occur where the fuel-air ratios are 0.064 or higher. NO_2 concentrations are lower than expected in this range probably due to lack of available oxygen in the combustion zone.

By convention, succeeding figures present NO_x concentrations in terms of NO_2 emission index values. NO emission index values can be obtained by using the curve of figure 8 and the ratio of molecular weights of NO_2 and NO.

Effects of combustor equivalence ratio and inlet-air temperature on NO_x formation for all three combustor models are shown in figure 9. Equivalence ratios were calculated on the basis of all of the air and fuel supplied to the combustor. Variances in the NO_x values along the three inlet air temperature curves are not the result of data scatter but rather represent effects produced by changes in combustor reference velocity, inlet pressure, and flame stabilizer geometry. Effects of these parameters will be discussed collectively and individually in a subsequent section. Effects of inlet air temperature will also be discussed.

With combustor model 1 operated with 589 K inlet air, the emission index level increases from a value of about 3 at an equivalence ratio of 0.26 to a peak value of 6.5 at an equivalence ratio of 0.7 and then decreases and approaches a value of about 4.6 at an equivalence ratio of 1.028. The shape of the emission index curve is affected by many factors such as reaction rates, availability of free oxygen and reaction zone temperatures. A simplified, qualitative model explaining formation rates in the three fuel-air ratio zones based on combustion data and visual observations of swirl-can combustors in operation is as follows: At lower equivalence ratios, combustion proceeds rapidly and is completed a short distance from the module array since the major portion of combustion air is supplied through the modules. Combustion is generally restricted to the module wakes. Bypass air through the array recirculates in the module wakes mixing with the combustion gases thus reducing flame temperatures and NO_x formation. As equivalence ratio if increased, heat flux increases and flame is not restricted to the module wakes but propagates across the entire array. At this condition, highest reaction zone temperatures are probably attained and the rate at which NO_x is formed increases.

Further increases in equivalence ratio cause additional effects to occur which cause the formation rate of NO_x to decrease. As fuel-air ratio is increased, more of the oxygen is used in combustion and becomes unavailable for NO_x formation. Also, the added fuel causes the fuel-air ratio in the vicinity of the modules to become overly rich thus reducing reaction zone

temperatures and NO_x formation. Accompanying the decrease in reaction
zone intensity is an elongation of the reaction zone along the combustor axis.
Thu hot gases have less combustor length to traverse and their residence
time in the combustor decreases. This condition appears to exist for equi-
valence ratios between 0.7 to 0.96. Within this span combustor exit tem-
perature continues to increase to a maximum value of 2322 K while emission
index values decrease. Parts per million values increase at a decreasing
rate to a maximum value of 216 ppm at an equivalence ratio of 0.944. Fur-
ther increases in equivalence ratio higher than 0.96 indicate that additional
oxygen is not available since combustor exit temperatures decreases rather
than increase. The other combustor models performed in a similar manner
as evidenced by the other data points contained on figure 9.

Unburned hydrocarbons and carbon monoxide. - Combustion inefficiencies
produced by unburned hydrocarbons and carbon monoxide plotted against
equivalence ratio for a 589 K inlet-air temperature are presented in figure 10.
Only combustor model 1 data are presented since they are representative of
values obtained with all combustor models. The inefficiency values were
obtained by calculating the changes in heating values resulting from the pol-
lutants. The calculation assumed that a carbon monoxide emission index of
42.7 represented a 1 percent inefficiency. Total hydrocarbons, which were
assumed to be primarily CH_2, produced a 1 percent inefficiency for each
emission index value of 10.

Both pollutant values were high at the lowest equivalence ratios and
produced a combustion inefficiency of approximately 3.5 percent. Pollutant
values then decreased with increasing equivalence ratio. However, both
pollutant values again increased at the highest equivalence ratios investigated
probably because of a lack of available oxygen in the combustion zone. At
an equivalence ratio of 0.96 unburned hydrocarbons produced an inefficiency
of about 0.5 percent and carbon monoxide produced an inefficiency of 5 per-
cent.

Additional combustion efficiency, carbon monoxide and unburned hydro-
carbon concentrations data are contained in references 4 and 5.

Correlation of Oxides of Nitrogen Data

Subsequent sections discuss correlation of the oxides of nitrogen data presented in figure 9. The approach used is to present the combined correlation first to indicate its scope and then to discuss each of the parameters making up the combined correlation separately in subsequent sections.

Combined correlation. - Oxides of nitrogen levels plotted against the combined correlating parameter are shown in figure 11. For additional information, the three combustor models and inlet temperature data are identified by symbols. The correlation consists of the following parameters:

$p^{1/2}$ inlet pressure in atmospheres

T_{in}/T_d T_{in} is the combustor inlet air temperature. T_d is the standard day temperature of 288 K

T_{exit} combustor exit average temperature K

V_{ref} combustor reference velocity in meters per second

W.P.   combustor module wetted perimeter

The oxides of nitrogen values were correlated for the three combustor modules to within an emission index value of ±1. However the correlation is not applicable over the entire span of combustor equivalence ratios but breaks down at higher values. This can be seen more clearly in figure 12 which is a duplicate of figure 11 with several items added. The dashed lines represent deviations of ±1 in index value from the average correlation values. As can be seen, most of the data falls between these two curves. Major exceptions occur for the following: With 589 K inlet air, NO_x concentrations for equivalence ratios of 0.5 or less fall within the two curves. For 0.6 equivalence ratios, the data straddles the ±1 limits with the majority of the data outside the limits. As equivalence ratio is further increased the emission index values deviate further from correlated values. This occurs because at the higher equivalence ratios the formation rate of NO_x decreases. With 756 K inlet air deviations from correlated values occur only at equivalence ratios

over 0.7. Data at 0.6 equivalence ratios falls along the correlation line. Tests with 839 K inlet air were not extended to equivalence ratios over 0.46 so falloffs at higher equivalence ratios were not determined for this inlet-air temperature.

A prior attempt has been made to correlate a small portion of this data and was reported in reference 8. An analytical model based on discrete burning volumes in the wake of the swirl cans was used to develop a correlation. This correlation was successful only for fuel-air ratios of approximately 0.015 to 0.02. An additional correlation based on a partially stirred reactor correlated data for a fuel-air ratio span of 0.04 to stoichiometric. The middle span of fuel-air ratios of 0.02 to 0.04 was not correlated.

The correlation reported in this paper, though arrived at through different considerations than that reported in reference 8, produces essentially the same result----they show promise, add further insight and, at the same time indicate the need for further work.

Individual parameter effects. - Effects on oxides of nitrogen formation of the various parameters making up correlation were arrived at through parametric testing. Several of the parameters such as inlet temperature and pressure have been widely discussed in the literature. Effects of other parameters such as reference velocity and combustor exit temperature are less well known. The wetted perimeter term is probably restrictive to primary combustion systems such as swirl-can combustors and has not appeared previously in the literature. For completeness, all of the oxides of nitrogen data, even the higher equivalence ratio data that did not fit the correlation is included in subsequent plots.

Inlet pressure. - Due to a test facility pressure limitation of 6.5 atmospheres it was not possible to obtain a sufficient span of pressure data to establish a pressure correlating parameter. However a $p^{1/2}$ term, which has been widely discussed in current literature, appears to adequately correlate the relatively small span of experimental pressure data.

Inlet temperature. - The effect of combustor inlet-air temperature on oxides of nitrogen levels is shown in figure 13, plotted against the other parameters. The strong exponential effect of inlet temperature is readily apparent.

Reference velocity. - Figure 14(a) presents NO_x data at 589 K inlet air temperature for model 1 for a span of exit temperatures and three reference velocities. The data are plotted against with the reciprocal of reference velocity for constant exit temperatures in figure 14(b). Decreases in emission index level with increases in reference velocity are probably due to reduced dwell time of hot gases within the combustor.

Wetted perimeter. - The function of this parameter is to account for the variances in geometry between the three combustor models and thereby correlate their data. All combustors utilized 120 modules. For different module number arrays a number correction factor would have to be added. The effect of flame stabilizer wetted perimeter on NO_x levels is shown in figure 15 plotted against the other correlating parameters. The wetted perimeter is easily calculated for a swirl-can combustor or any other combustor design which consists primarily of a primary zone. However, for a more conventional combustor design consisting of a primary and secondary zone, this parameter would be difficult to calculate. For this reason a pressure loss parameter would be preferred. A pressure loss correlating parameter applicable to swirl cans has not been evolved to data. The wetted perimeter includes pressure loss in terms of combustor blockage area but also includes an interfacial mixing area component in terms of the flame stabilizer perimeter.

Combustor exit temperature. - The effect of combustor exit temperature on NO_x levels is shown in figure 16 plotted against the other correlating parameters. For clarity, symbols are included on each curve to indicate the inlet air temperature data each curve contains. These data further indicate the breakdown of the correlation at higher equivalence ratios with both 589 and 756 K inlet air.

SUMMARY OF RESULTS

Pollutant concentrations of three models of a full-annulus swirl-can combustor were measured. These included concentrations of nitric oxide, total oxides of nitrogen, unburned hydrocarbons and carbon monoxide. Test conditions were inlet-air temperatures of 589, 756 and 839 K, pressures of 3 to 6.4 atmospheres, reference velocities of 21 to 38 meters per second and combustor equivalence ratios of 0.206 to 1.028. The following results were obtained:

1. With 589 K inlet-air temperature the maximum emission index value of oxides of nitrogen occurred at an intermediate equivalence ratio of 0.7. Emission index values were lower for both higher and lower equivalence ratios.

2. Oxides of nitrogen concentrations were correlated for the three combustor models to within an emission index value of ±1 by the combined parameter $p^{1/2} e^{T_{in}/T_d} T_{exit}/V_{ref} W.P..$ The correlation is applicable up to combustor equivalence ratios of 0.7 with 756 K inlet air and to 0.6 with 589 K inlet air.

3. Effects of the individual parameters, with the exception of pressure, on oxides of nitrogen concentration have been determined.

CONCLUDING REMARKS

The correlation presented is not intended to represent a definitive final statement defining factors affecting oxides of nitrogen formation. Rather, the correlation represents a first attempt at defining a complex mechanism. The data and parametric considerations are imminently current and in a process of evolution. Subsequent efforts will concentrate on further defining better exponents for the parameters, making the parameters more general and therefore applicable to more types of combustion systems, and defining a mechanism applicable to oxides of nitrogen formation at high equivalence ratios.

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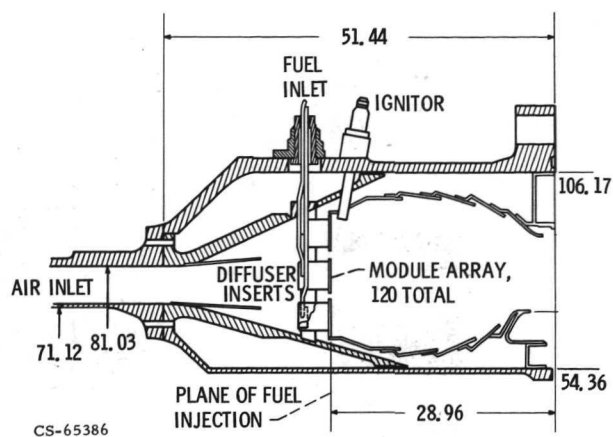
Figure 1. - Full annular model of high-temperature combustor.
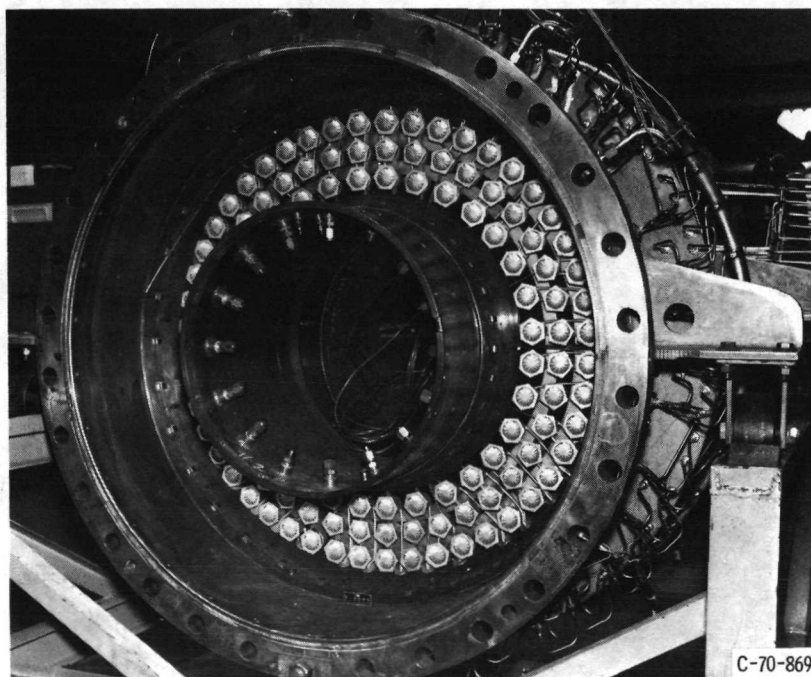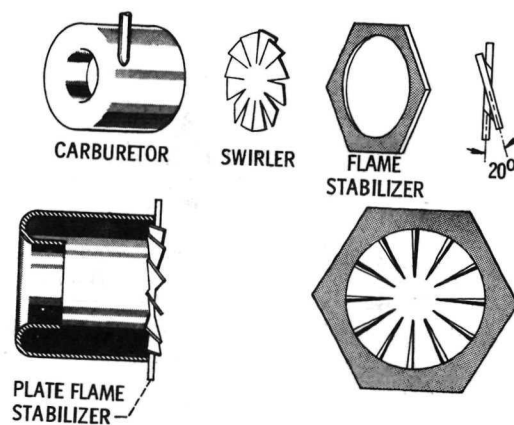(Dimensions in centimeters.)

Figure 2. - Annular swirl-can-modular combustor.

CARBURETOR SWIRLER FLAME STABILIZER 20°

PLATE FLAME STABILIZER

CS-56698

Figure 3. - Combustor module details. (Dimensions in centimeters.)

MODEL I

C-73-1864

MODEL II

MODEL III

CS-66805

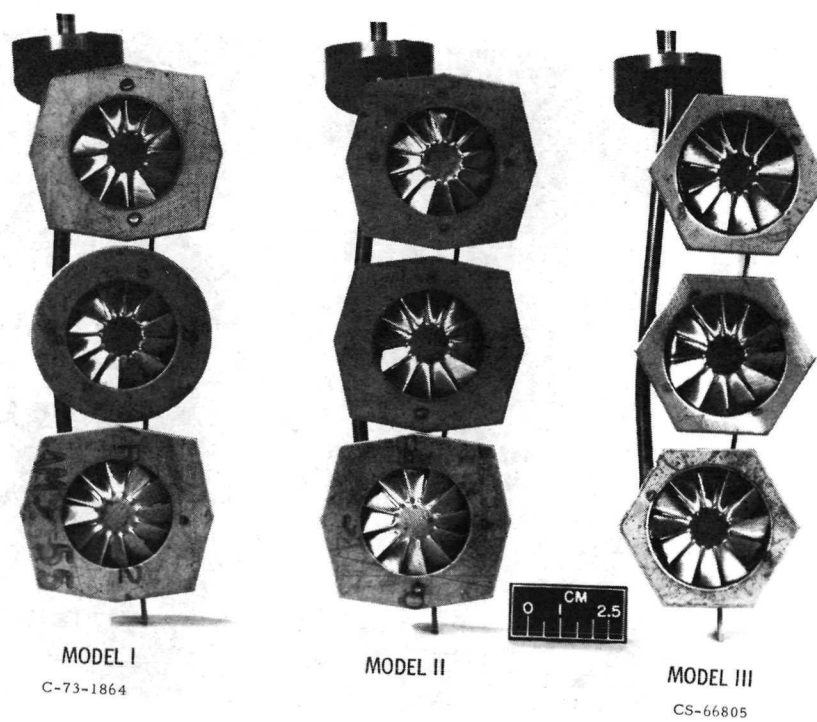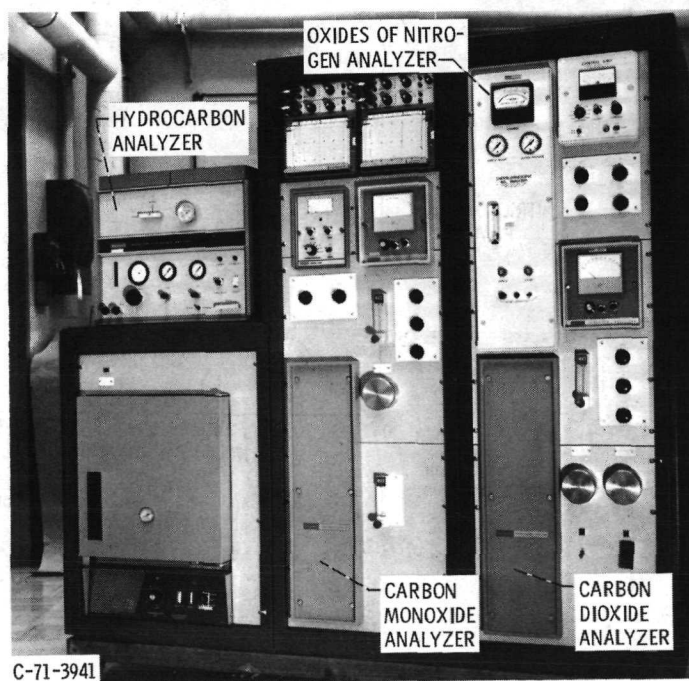Figure 4. - Combustor modules for the 3 combustor models.

C-71-3378

Figure 5. - Three-point gas sampling probe with water-cooled jacket.
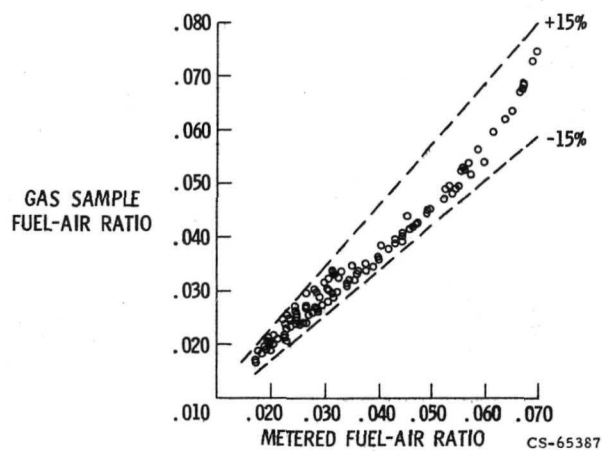

Figure 6. - Exhaust gas analysis system.

.080
.070
.060
.050
.040
.030
.020
.010

GAS SAMPLE
FUEL-AIR RATIO

+15%
−15%

.020 .030 .040 .050 .060 .070
METERED FUEL-AIR RATIO   CS-65387

Figure 7. - Sample validity check.

500
400
300
200
100

NITRIC OXIDE,
PPM

F/A > 0.064

INLET,
K

○ 589
□ 756
△ 839

0   100   200   300   400   500   600
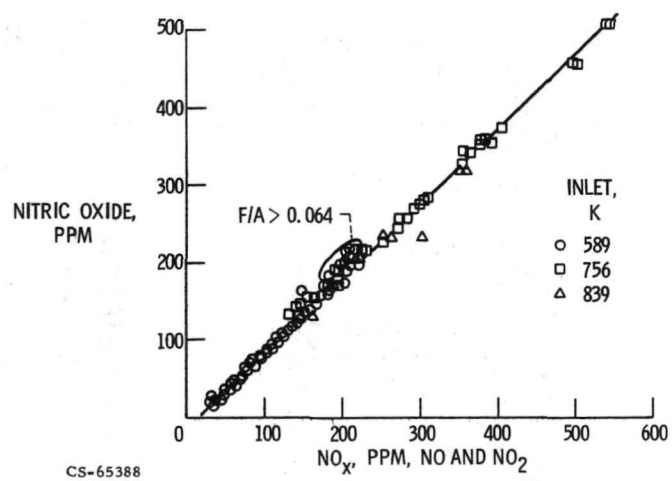NO_x, PPM, NO AND NO_2

CS-65388

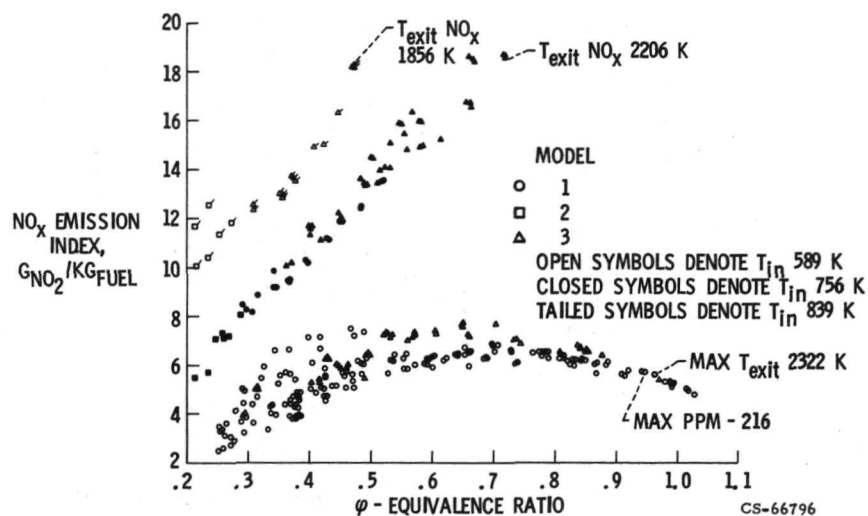Figure 8. - No and NO_x concentrations.

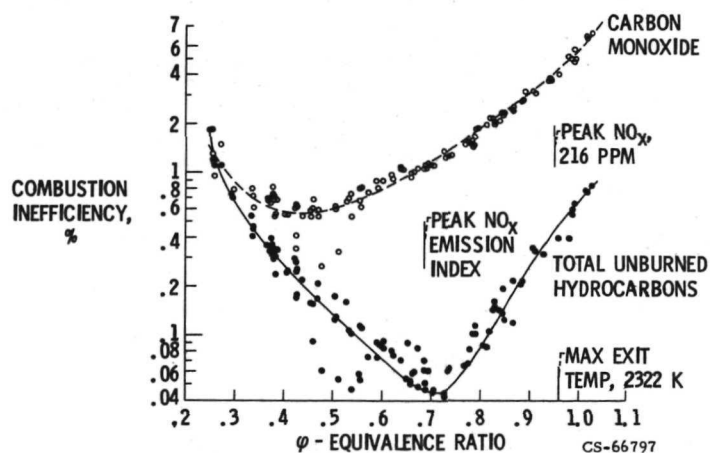Figure 9. - Oxides of nitrogen concentrations for combustor models 1, 2, and 3.

Figure 10. - Combustion inefficiency as a function of carbon monoxide, total unburned hydrocarbons and equivalence ratio. Combustor model 1. Inlet air temperature, 589 K.
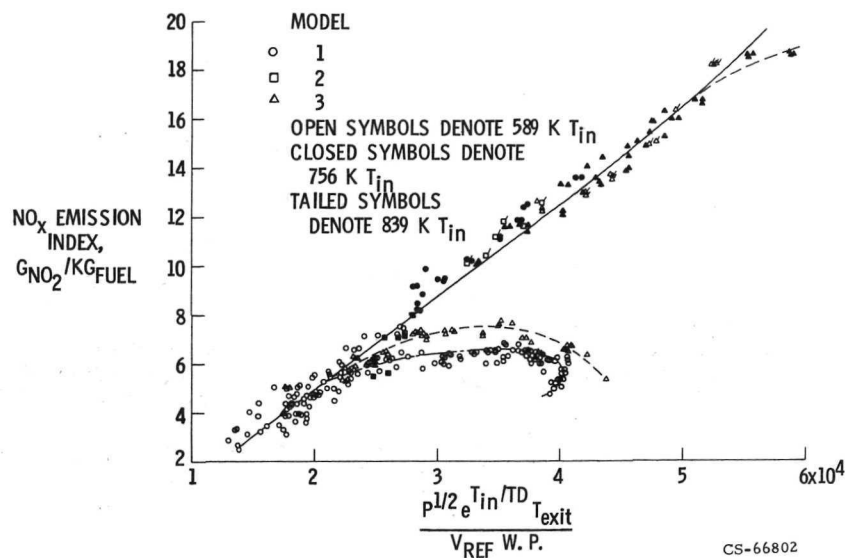
MODEL
○ 1
□ 2
△ 3
OPEN SYMBOLS DENOTE 589 K T_{in}
CLOSED SYMBOLS DENOTE
756 K T_{in}
TAILED SYMBOLS
DENOTE 839 K T_{in}

NO_x EMISSION INDEX, G_{NO_2}/KG_{FUEL}

20
18
16
14
12
10
8
6
4
2

1   2   3   4   5 6×10^4

$$\frac{P^{1/2} e^{T_{in}/TD} T_{exit}}{V_{REF} \ W.P.}$$

CS-66802

Figure 11. - Oxides of nitrogen correlation.

MODEL
○ 1
□ 2
△ 3
OPEN SYMBOLS DENOTE 589 K
CLOSED SYMBOLS DENOTE 756 K
TAILED SYMBOLS DENOTE 839 K

CORRELATION CURVE
OF FIG 11

$\varphi = 0.7$
$T_{in} = 756$ K

$\varphi = 0.6$
$T_{in} = 756$ K

+1 EMISSION INDEX VALUE

-1 EMISSION INDEX VALUE

$\varphi = 0.5$
$T_{in} = 589$ K

$\varphi = 0.5$
$T_{In} = 589$ K

$\varphi = 0.7$
$T_{in} = 589$ K

$\varphi = 0.8$ OR GREATER
$T_{in} = 589$ K

$\varphi = 0.6$
$T_{in} = 589$ K

NO_x EMISSION INDEX, G_{NO_2}/KG_{FUEL}

20
18
16
14
12
10
8
6
4
2

1   2   3   4   5 6×10^4

$$\frac{P^{1/2} e^{T_{in}/TD} T_{exit}}{V_R \ W.P.}$$

CS-66803

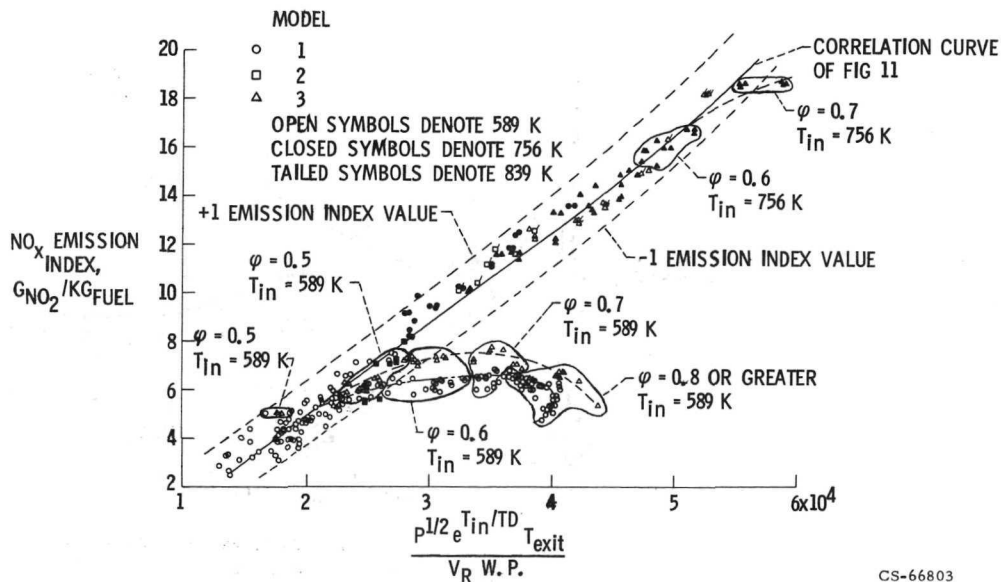Figure 12. - Breakdown of correlation of higher equivalence ratios.

Figure 13. - Effect of inlet air temperature on oxides of nitrogen levels.

(a) NO$_x$ EMISSION INDEX VS COMBUSTOR EXIT TEMPERATURE FOR 3 REFERENCE VELOCITIES.

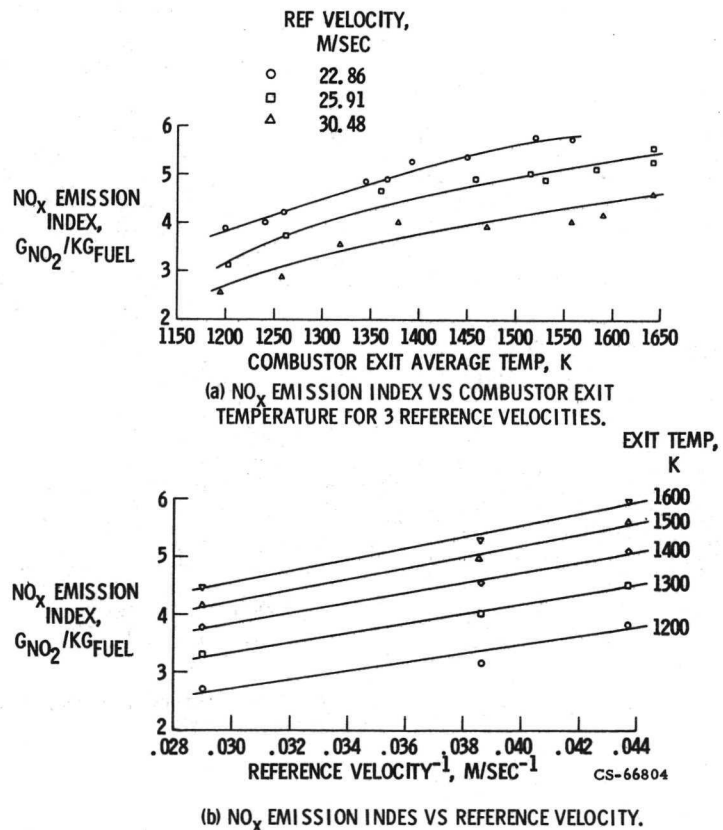(b) NO$_x$ EMISSION INDES VS REFERENCE VELOCITY.

Figure 14. - The effect of combustor reference velocity on oxides of nitrogen concentration. Combustor model 1. Inlet air temperature 589 K; inlet pressure 6 atm.
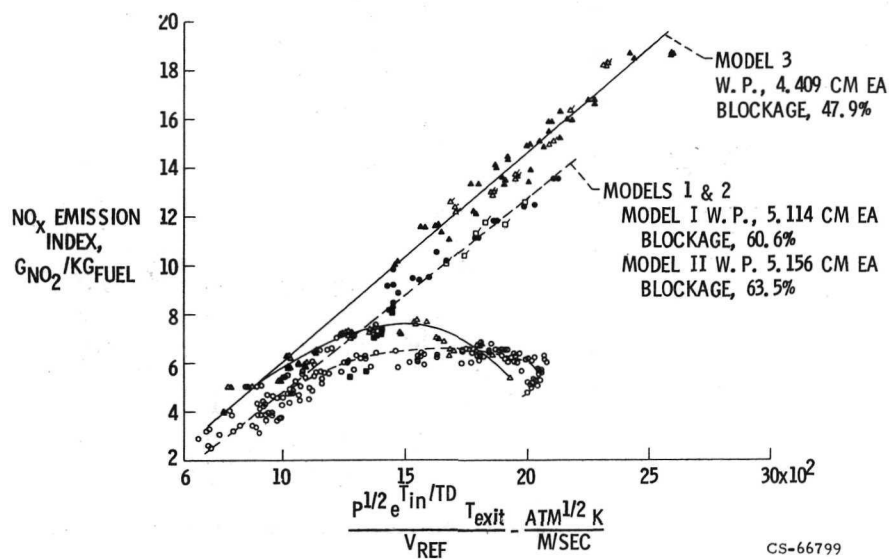
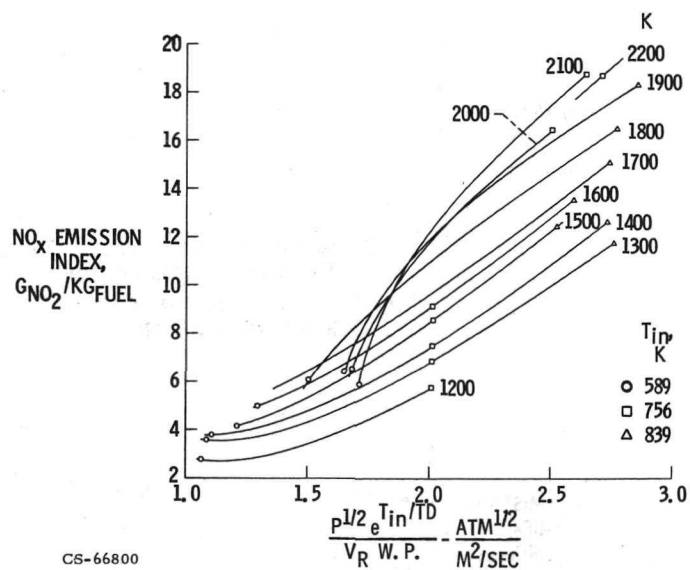Figure 15. – Effect of flame stabilizer geometry on oxides of nitrogen levels.

MODEL 3
W. P., 4.409 CM EA
BLOCKAGE, 47.9%

MODELS 1 & 2
MODEL I W. P., 5.114 CM EA
BLOCKAGE, 60.6%
MODEL II W. P. 5.156 CM EA
BLOCKAGE, 63.5%

NO_x EMISSION INDEX, G_{NO_2}/KG_{FUEL}

$$\frac{P^{1/2} e^{T_{in}/TD} T_{exit}}{V_{REF}} - \frac{ATM^{1/2} K}{M/SEC}$$

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Figure 16. – Effect of combustor exit temperature on oxides of nitrogen levels.

NO_x EMISSION INDEX, G_{NO_2}/KG_{FUEL}

K
2200
2100
1900
2000
1800
1700
1600
1500
1400
1300
1200

T_{in}, K
○ 589
□ 756
△ 839

$$\frac{P^{1/2} e^{T_{in}/TD}}{V_R \ W. P.} - \frac{ATM^{1/2}}{M^2/SEC}$$

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